EFFECTS OF A WAVY NEUTRAL SHEET ON COSMIC RAY ANISOTROPIES

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Abstract. We present the first results of our 3-D numerical code calculating cosmic ray anisotropies. The code includes diffusion, convection, adiabatic deceleration, and drift in an interplanetary magnetic field model containing a wavy neutral sheet. We find that the 3-D model can reproduce all the principal observations for a reasonable set of parameters.

Introduction. In the last decade, the effects of curvature and gradient drifts became a central issue in the theory of cosmic ray transport. It has been suggested that drift may play an important, and perhaps dominant, role in cosmic ray propagation in the heliosphere, and it may be responsible for the asymmetries appearing in consecutive 11-year cycles (Jokipii, Levy and Hubbard, 1977; Jokipii and Kopriva, 1980; Kótá, 1979; Jokipii and Thomas, 1981; Kótá and Jokipii, 1983). The first success of drift models in explaining galactic cosmic-ray phenomena was the explanation of the phase shift of the solar daily variation (Levy, 1976) observed in the years of the seventies, following the polarity reversal of the solar magnetic field. The first quantitative 2-dimensional (2-D) calculation was carried out by Jokipii and Kopriva (1980). In this work, however, the too small value of the diffusion coefficient, \( \kappa \), led to unreasonable anisotropies in some cases. Kótá (1981) derived an approximate force-field solution with a virtually perfect isotropy. This model, however, relied upon the too simple picture of 'hard-sphere' scattering.

The well-known phase shift of the solar daily variation (Duggal and Pomerantz, 1975) is naturally explained by 2-D models (Levy, 1976; Kadokura and Nishida, 1984). The magnetic configuration of the seventies (\( A>0 \)) yields a smaller radial density gradient which cannot balance the convection by the solar wind and thus results in a net outward streaming. Another well-established observation is the presence of the polarity dependent N-S anisotropy associated with the \( \mathbf{B} \times \mathbf{v} \) drift (Bercovitch, 1970; Pomerantz and Bieber, 1984). In the seventies (\( A>0 \)), this streaming is directed away from the neutral sheet. In a 2-D model, this pattern of streaming is hard to reconcile with the \( \text{div} \mathbf{S} < 0 \) requirement, thus 2-D models are bound to encounter difficulties in explaining both observations.

The basic difficulty, in principle at least, may be removed if, violating the axial and N-S symmetries, a wavy neutral sheet is included. It is the purpose of this work to demonstrate that a 3-D model is indeed able to reproduce all components of the observed anisotropies. We present the first anisotropy results of our 3-D code incorporating a wavy neutral sheet.

The Model. We used a 3-D numerical code to solve the modulation equation including diffusion, convection, adiabatic deceleration and drift. The model and the scheme of calculation were described in detail elsewhere (Kótá and Jokipii, 1983, see also the preceding paper SH-4.2-10 in this issue). Briefly, a usual spiral field is adopted, the magnetic equator is a tilted plane at the sun, which then evolves into a wavy sheet (Jokipii and Thomas, 1981). The case of \( A>0 \) corresponds to outward polarity above...
the sheet and inward polarity below the sheet while A<0 corresponds to
the opposite configuration (sixties and eighties). Steady state is
assumed in the frame corotating with the sun. The most serious limitation
of the code is that it assumes constant solar wind speed thus many
phenomena, like shocks, are precluded.
Calculations were carried out for protons in the 1 - 10 GV range. The
parallel diffusion coefficient, \( \kappa_\parallel \), was assumed to be inversely
proportional to the magnetic field strength, \( B \),

\[
\kappa_\parallel = K_0 P^{1/2} \rho (B_{\text{earth}}/B)
\]

with \( P \) being the particle rigidity in GV, \( \rho \) is the particle velocity
in units of velocity of light, \( B \), and \( K_0 \) is a normalization constant in
the range of \( 10^{21} - 10^{23} \text{ cm}^2/\text{sec} \). The ratio of the perpendicular and
parallel diffusion coefficients was kept constant at \( \kappa_\perp/\kappa_\parallel = 0.05-0.20 \).

Results and Discussion Anisotropies were calculated at three
heliocentric distances (0.5, 1, and 5 AU) over the full range of
heliographic latitudes and longitudes. Here, we present the results near
the earth. The anisotropies to be reported are obtained at the
helioequator, at 1 AU, and averaged over longitudes in a magnetic sector.

The ecliptic components of the anisotropy responsible for the solar
daily variation are given in Figures 1 and 2 \( (P=2.3 \text{ GV}; \kappa_\parallel/\kappa_\perp = 0.05) \). It
should be noted that the anisotropies obtained for a flat sheet (dashed
lines) show sharp changes at the neutral sheet. The actual values (dots)
may considerably differ from the averages over a \((-50, 50) \text{ latitude band}
(open circles). In most cases, \( A>0 \) gives an earlier phase and a slower
amplitude which is in general agreement with observations. Similar re-
sults were obtained for other rigidities, too. At large values of \( K_0 \),
understandably, drift effects diminish and a near perfect corotation
applies. The breaks in the lines in the \( K_0 = 1.5-5.10^{22} \text{ cm}^2/\text{sec} \) range
indicate that corotation should be reached somewhere in this interval.

Figure 3 shows \( \xi_x \), the zenith angle component of the average near
earth anisotropy above the neutral sheet for \( P = 2.3 \text{ GV} \). Consider first
the case \( A>0 \), when the 'observed' value of \( \xi_x \) is negative in accordance
with the sense of the \( \mathbf{B} \times \mathbf{V}_n \) streaming. Curve (a) corresponding to \( \kappa_\parallel/\kappa_\perp = 0.05 \) and \( \alpha = 150^\circ \) yields the correct sign for \( \xi_x \). Larger tilt angle \( \alpha = 30^\circ \), curve (b)), however, may already give positive values, too. If we
take, on the other hand, a larger perpendicular diffusion (curve (c):
\( \kappa_\perp/\kappa_\parallel = 0.20, \alpha = 30^\circ \) \( \xi_x \) will again point in the proper direction for all
values of \( K_0 \). The underlying physical picture is that, in the case of
large tilt angles and small perpendicular diffusion, most particles reach
the earth without having interacted with the neutral sheet. Being too
far from the earth, the neutral sheet becomes irrelevant for \( A>0 \). As for
\( A<0 \), particles intersect the sheet several times before reaching the
earth. As a result, the calculated \( \xi_x \) always shows the proper sense and
is fairly independent of the tilt angle \( \alpha \).

Figure 4 indicates that the magnitude of \( \xi_x \) increases and its sign
becomes more distinctive with increasing rigidities. This finding can
also be anticipated since drift effects are expected to be more
pronounced at higher rigidities.

The typical azimuthal dependence of the N-S anisotropy is presented
in Figure 5. In most cases, we cannot find a one-to-one correspondence
between the sign of \( \xi_x \) and the polarity of the field. In general, smaller
tilt angle, and larger \( \kappa_\parallel \) results in a better correlation; the
correlation also improves at higher rigidities. At 5 AU heliocentric distance, virtually all our runs gave a 100 percent correlation. To interpret this, we note that the waves in the neutral sheet become relatively tighter at larger distances from the sun. Thus we expect the effects of waviness to be more direct there.

**Conclusion.** Our numerical results demonstrate that the inclusion of a wavy neutral sheet may explain all components of the observed anisotropies. We find a general agreement between 'theoretical' and 'observed' anisotropies for a wide range of parameters. At high latitudes, well above or below the sheet, however, we predict the anisotropy to point toward the equator in the case of $A>0$. This is in contrast to the poleward direction expected from the $B \times Vn$ term only.

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**References.**

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![Figure 1](image)

**Figure 1.** Radial and azimuthal components of the average near earth anisotropy calculated for $A>0$, $P=2.3$ GV, $K_p/K_n=0.5$. Dashed and solid lines refer to flat (see text) and wavy sheets, respectively. $K_p$ is in units of $10^{22}$ cm$^2$/sec. The phases of the resulting daily waves are also shown.
Figure 2. Same as Fig. 1., for $A < 0$.

Figure 3. The average value of $\xi_{\phi}$ for the earth being above the neutral sheet. $P=2.3$ GV, $K_0$ is in units of $10^{22}$ cm$^2$/sec.
(a) $\kappa_2/\kappa_3=0.05$, $\alpha = 150^\circ$;
(b) $\kappa_2/\kappa_3=0.05$, $\alpha = 300^\circ$;
(c) $\kappa_2/\kappa_3=0.20$, $\alpha = 300^\circ$.

Figure 4. $\xi_{\phi}$ vs rigidity calculated for $K_0=10^{22}$ cm$^2$/sec, $\kappa_2/\kappa_3=0.05$.

Figure 5. Azimuthal dependence of $\xi_{\phi}$ calculated for $P=2.3$ GV, $\kappa_2/\kappa_3=0.05$.
(a) $A > 0$, $\alpha = 150^\circ$; (b) $A > 0$, $\alpha = 300^\circ$;
(c) $A < 0$, $\alpha = 150^\circ$. 